



Transcranial electric motor evoked potential monitoring during scoliosis surgery in children with cerebral palsy and active seizure disorder: is it feasible and safe?

M. Wade Shrader¹ · Sabina DiCindio² · Katherine G. Kenny³ · Alier J. Franco⁴ · Ran Zhang¹ · Mary C. Theroux¹ · Kenneth J. Rogers¹ · Suken A. Shah¹

Received: 21 December 2022 / Accepted: 24 June 2023 / Published online: 17 July 2023
© The Author(s), under exclusive licence to Scoliosis Research Society 2023

Abstract

Purpose Use of spinal cord monitoring in children with cerebral palsy (CP) and neuromuscular scoliosis is challenging. The previous reports suggest low success rates in the setting of CP, and it is unclear if transcranial electric motor evoked potentials (TcMEP) monitoring is contraindicated in patients with an active seizure disorder. The purpose of this study was to determine (1) are patients with CP able to be appropriately monitored with TcMEP? and (2) does TcMEP cause an increase in seizure activity?

Methods This was an institutional review board-approved retrospective cohort study observing 304 patients from 2011 to 2020. Inclusion criteria included all patients with CP undergoing posterior spinal fusion during this time. Intraoperative data were examined for the ability to obtain monitoring and any intraoperative events. Patients were followed for 3 months postoperatively to determine any increase in seizure activity that could have been attributed to the TcMEP monitoring.

Results Of the 304 patients who were observed, 21% (20.8%) were unable to be monitored due to lacking baseline signals from the extremities. Seventy-seven percent (77.5%) were successfully monitored with TcMEP. For these patients, no increased seizure activity was documented either intra- or postoperatively.

Conclusion A high percentage of children (77.5%) with CP were able to be successfully monitored with TcMEP during posterior spinal fusion. Furthermore, the concerns about increased seizure activity after TcMEP were not supported by the data from this cohort. Technical details of successful neuromonitoring in these patients are important and included increased stimulation voltage requirements and latency times.

Level of evidence III retrospective comparative study.

Keywords Transcranial electric motor evoked potentials · Neuromuscular scoliosis · Seizure disorder · Epilepsy · Cerebral palsy

Introduction

Intraoperative neurophysiological monitoring (IONM) for detecting and preventing impending neurologic deficit during spinal deformity surgery has grown significantly since the seminal report by Nash et al. [1], which described somatosensory evoked potentials (SSEP) to monitor spinal cord function. Over the past two decades, use of a single modality, SSEP, for monitoring spinal cord function has given way to a multimodal approach, which commonly includes transcranial motor evoked potentials (TcMEP), SSEP, and/or both spontaneous and electrically triggered electromyography [2].

✉ M. Wade Shrader
Wade.shrader@nemours.org

¹ Department of Orthopaedics, Nemours Children's Health, 1600 Rockland Road, Wilmington, DE 19803, USA

² Sidney Kimmel Medical College, Thomas Jefferson University, Philadelphia, PA, USA

³ University of South Carolina, Columbia, SC, USA

⁴ Greater Delaware Valley Specialty Care, Philadelphia, PA, USA

Somatosensory evoked potentials, which have been routinely used for more than 30 years, can provide information about dorsal column function but are limited in several ways. Perhaps most importantly, SSEP are unable to detect injury localized to the anterior and anterolateral spinal cord or to individual nerve roots and sometimes change only after a significant delay in spinal cord ischemia. More recently, TcMEP have emerged as a highly sensitive tool for monitoring the lateral corticospinal tracts, giving a more complete picture of spinal cord function. Indeed, a great deal of evidence has accumulated demonstrating improved efficacy of spinal cord monitoring resulting from the use of TcMEP in conjunction with SSEP compared with SSEP alone [2–5]. When used together, SSEP and TcMEP can achieve combined sensitivity and specificity for the prediction of spinal cord injury approaching 100% [6]. A multimodality approach to IONM has become an accepted standard of care during correction of pediatric spinal deformity [6].

The etiology of a patient's scoliosis impacts the practical implementation of this standard of care. In patients with neuromuscular disorders, both the efficacy and the safety of TcMEP, more specifically repetitive high-voltage transcranial electric stimulation (RTES), have been discussed at length [7–9]. This debate has been complicated by the fact that there are specific subpopulations of patients whose baseline neurological pathology makes establishing a neuromonitoring baseline more difficult, placing them at increased risk of developing iatrogenic injury [10]. Moreover, many of these patients historically have not been considered candidates for neuromonitoring using TcMEP due to perceived contraindications. In particular, a history of seizure disorder has been cited as a contraindication due to theoretical concerns over epileptogenic properties of RTES [2, 11–13].

Cerebral palsy (CP) is a common neuromuscular disability that frequently has comorbidities of epilepsy and scoliosis. Intraoperative neuromonitoring is often difficult due to the complex neurological pathology. Two large multi-state epidemiological studies suggest that the prevalence of CP among 8 years old (the age at which CP prevalence peaks) is approximately 3.1–3.6 out of every 1000 children [14, 15]. Of those diagnosed, spastic CP is the most common form, accounting for 61–77% of cases. The incidence of epilepsy in CP is reported to be 20–40%, and epilepsy is most common in spastic CP with hemi- or quadriplegia, with some studies reporting rates as high as 80% [16–19]. Scoliosis is another common comorbidity associated with spastic quadriplegic CP, and estimates range from 30 to 80% in this subpopulation [20, 21]. Non-ambulatory children who are dependent sitters (Gross Motor Functional Classification System level V) are at highest risk for developing progressive scoliosis. The effectiveness of spinal cord monitoring with SSEP alone during correction of neuromuscular

scoliosis (NMS) has been questioned because of limited reliability as well as an unacceptably high false-positive rate in this patient population [9, 10, 22].

This study sought to assess the feasibility, effectiveness, and safety of TcMEP monitoring in patients with spastic quadriplegic CP undergoing correction of NMS.

Methods

This was an institutional review board-approved retrospective cohort study that analyzed the medical charts of 304 consecutive patients with CP who underwent correction of NMS at a single institution from 2011 to 2022. Of the 304 patients who were observed, monitoring was attempted in 231 (77.5%). Seventy-three patients in the earlier years of the study period were not attempted due to senior surgeon preference; this approach was primarily due to concerns about limited actionable clinical utility in the setting of potentially unreliable monitoring of a severely neurologically disabled child. This group was used as an internal control to determine the rate of increased seizure activity postoperatively. With improved modern IONM techniques, the standard at our institution has been to attempt neurological monitoring in all children, regardless of their diagnosis, since 2017.

All patients underwent posterior spinal fusion with instrumentation from T1 or T2 to the sacrum, including pelvic fixation. Early in the study period, patients were instrumented with Luque wire fixation (unit rod) or with pedicle screws. After 2017, all patients had segmental pedicle screw fixation. Patients followed a similar postoperative pathway for perioperative management.

The nature of specific neurological diagnoses of patients with CP was used to predict the ability to obtain usable TcMEP. Neurological imaging diagnoses (from computed tomography and/or magnetic resonance imaging scans) assessed were corpus callosum abnormalities, cortical and deep gray matter damage, encephalomalacia, hydrocephalus, lissencephaly, periventricular leukomalacia, porencephaly, traumatic brain injury, and no imaging available.

Intraoperative monitoring was treated as a dichotomous variable, and logistic regressions were estimated for the model: $\text{logit}\{\pi(x_i)\} = \alpha + \beta_i x_i$. The logistic model was optimized by p value at the level of 0.05.

Anesthetic management

Following preoxygenation, anesthesia was induced with propofol. After induction, additional peripheral intravenous, arterial, and central venous lines were placed as needed. Anesthesia was then maintained using total intravenous anesthetic technique via a continuous infusion of propofol and a narcotic, typically sufentanil or remifentanil. If the

patient had reliable signals, then anesthesia was maintained using total intravenous anesthetics via a continuous infusion of propofol and a narcotic, typically sufentanil or remifentanyl. If the patient did not have recordable signals, then the anesthetic was left to the discretion of the anesthesiologist. No neuromuscular blocking agents were used following surgical exposure to optimize transmission across the neuromuscular junction during motor evoked potential testing. Additional details of standard anesthetic management for these patients have been described elsewhere [2].

IONM

Intraoperative neuromonitoring was performed as the standard procedure at our institution for all patients. Multimodality spinal cord monitoring was conducted using commercially available neuromonitoring workstations (Endeavor, Nicolet Biomedical, Madison, WI; Epoch or Eclipse, Axon Systems, Hauppauge, NY). Monitoring was initiated following induction and continued through wound closure. Cortical and subcortical SSEP were elicited to 300-microsecond duration square-wave electrical pulses delivered in interleaving fashion to the left and right posterior tibial nerves at a rate of 4.7 stimulations per second. Cortical potentials were recorded from Cpz referenced to Fpz (international 10–20 system). Subcortical cervical/brainstem potentials were recorded over the surface of cervical vertebrae 2 or 3 and also referenced to Fpz. In addition, SSEP to ulnar nerve stimulation were recorded to detect evolving peripheral nerve injury secondary to upper extremity positioning. Two channels of electroencephalography (EEG) were recorded throughout the procedure, typically between scalp locations Cp3-Fpz and Cp4-Fpz, to screen for intraoperative seizure activity and aid in anesthesia management.

The TcMEP were triggered using high-voltage, anodal electrical pulse trains (300–500 V, pulse width 50–75 microseconds, and 3–7 pulses per train with interpulse intervals of 1–4 ms). This stimulus was delivered between two subdermal electrodes that were placed over the motor cortical regions at C1 and C2 (international 10–20 system). The electrical pulses were generated by a D185 stimulator

(Digitimer, Welwyn Garden City, UK) or the internal stimulator of the Axon Eclipse workstation. Stimulation parameters were optimized for each patient to trigger suprathreshold TcMEP of sufficient size and consistency for reliable monitoring. The bilateral recording montage included at least two myotomes in the lower extremities, most commonly the tibialis anterior and abductor hallucis muscles, and the first dorsal interosseous muscle in the hands.

Results

Of the 231 patients who had IONM attempted, 48 patients (20.8%) were not able to be monitored because they lacked baseline signals from the extremities (no TcMEP or SSEP), and four patients (1.7%) had lower extremity SSEP but no motors. One hundred and seventy-nine of the 231 patients (77.5%) were successfully monitored with TcMEP.

One hundred and sixty-eight patients (72.7%) in the study cohort had a seizure disorder, which was very similar to 54 patients (74.0%) in the control group. No physical or EEG manifestation of intraoperative seizure activity was evident in any of the 179 patients who were monitored using TcMEP. Three patients in the study group (1.3%) and two patients in the control group (2.7%) had increased seizures postoperatively (Table 1). This was not statistically significant ($p=0.88$) with Chi-squared analysis.

Twenty-six (11.3%) patients had temporary loss of motor signals during the procedure. All had return to normal baseline signals with standard intraoperative protocols including increasing the mean arterial pressure, changes in anesthetic technique, and checking the IONM leads. No change in baseline neurological function occurred in patients who had IONM. Two children in the control group had postoperative changes in their neurological function with increased spasticity and changes in bowel and bladder function.

The optimized logistic regression model showed that the neurological imaging diagnoses of hydrocephalus, traumatic brain injury, and no imaging available were strongly associated with the ability to obtain TcMEP ($p < 0.05$) when compared with the other variables.

Table 1 Comparison of group 1 (IONM) with the control group 2 (no IONM attempted)

Group (<i>n</i>)	IONM	Number of patients (%)	Number of patients with seizures at time of surgery (%)	Number of patients with increase in seizures postoperatively
Group 1 (231)	TcMEP, SSEP, and EEG	179 (77.5)	126 (70.4)	2
Group 1 (231)	No baseline	48 (20.8)	41 (85.4)	1
Group 1 (231)	No TcMEP	4 (1.7)	1 (25.0)	0
Group 2 (73)	No monitoring	73 (100.0)	54 (74.0)	2

EEG electroencephalography, IONM intraoperative neuromonitoring, SSEP somatosensory evoked potentials, and TcMEP transcranial electric motor evoked potentials

Discussion

In this study, spinal cord function was monitored successfully using a combination of SSEP and TcMEP modalities for 77.5% of patients with CP. While the total number of patients for whom IONM was possible was expectedly lower in this population than the population of adolescent idiopathic scoliosis patients [2, 7], given the pre-existing neuromuscular pathology, the data nonetheless suggest that most NMS patients were potential beneficiaries of spinal cord monitoring during corrective spine surgery.

Importantly, IONM was carried out without any documented physical or EEG evidence of intraoperative seizure activity. As noted by DiCindio et al. [2], patients with NMS present many challenges to reliable and valid spinal cord monitoring. These researchers published data in 2003 demonstrating that spinal cord function could be monitored reliably using both SSEP and TcMEP; however, the theoretical concern that RTES could elicit seizure activity precluded TcMEP monitoring in NMS patients with a history of seizure disorder. Our results confirm their findings on the feasibility of monitoring. Moreover, the present results provide evidence that RTES for triggering of motor evoked potentials is safe in patients, even those with an active seizure disorder.

It is important to note that although the contraindication for use of TcMEP in patients with a history of seizure disorder has been widely cited, there is no published evidence to support this contraindication [2, 6, 8, 11–13]. In an extensive review of more than 15,000 cases from published reports as well as unpublished personal communication, MacDonald [12] describes five instances of intraoperative seizures during cases in which TcMEP were used, all reported through personal communication. Although this number is not negligible, MacDonald states that it is unclear whether it reflects a greater likelihood than that of spontaneous seizures and concludes that seizures are clearly very rare following RTES for triggering of motor evoked potentials compared with other types of brain stimulation methods. The results of the present study, smaller in scope but with a standardized technique, provide safety data on TcMEP monitoring of seizure-prone patients that are consistent with the findings for the population at large.

In an often-cited survey conducted by Legatt [11], most centers using TcMEP during IONM included “history of seizure disorder” among their patient exclusion criteria. However, in the same article, Legatt describes only two reported intraoperative seizures, both of which occurred in patients with a history of seizure disorder who were described as “under medicated,” and only one of which was temporally associated with the use of TcMEP.

Due to the perception that TcMEP are contraindicated in patients with seizure disorder, Master et al. [13] recently explored the efficacy of SSEP-only monitoring for scoliosis correction in eight patients with Rett syndrome. They reported successful monitoring for all eight with seven true-negative and one true-positive outcomes. In contrast, several larger studies have concluded that SSEP alone are insufficient for spinal cord monitoring during deformity correction in patients with NMS [9, 10].

The importance of determining relative safety of TcMEP monitoring in patients with a history of seizures is highlighted by a recent retrospective study examining the efficacy of IONM in NMS cases [8]. In that study, two of 58 monitored patients emerged with postoperative deficits that were not identified by intraoperative signal changes. Importantly, TcMEP were not utilized in either case because of stated concerns that their use was contraindicated due to history of epilepsy.

The issues of balancing risk and benefit of IONM in children with severe neurological disabilities are complex and certainly have impacted the choice of monitoring these children intraoperatively in the past. However, we feel that this study has shown that the risk of seizure activity from TcMEP was not increased in this patient population, and the overall majority of patients with CP can be successfully monitored thereby possibly decreasing the risk of postoperative neurological deficits.

The present study has several limitations. Its retrospective nature and the relatively small sample size precluded establishing the intraoperative incidence of EEG and clinical seizures in the two cohorts. This study cohort was also studied at a single institution; monitoring techniques vary greatly among different institutions, so it is unclear how generalizable are these data. While the data suggest that TcMEP monitoring is feasible and safe in the studied population, demonstration of the benefits of monitoring requires further investigation, including long-term patient follow-up as well as a true cost–benefit analysis.

In conclusion, the perception that TcMEP are contraindicated in patients with a history of seizure disorder has persisted despite the absence of supporting published data. The incidence of epilepsy in patients with NMS secondary to CP is particularly high, and these patients experience an elevated risk of developing postoperative neurologic deficit following scoliosis correction. In the present study, no physical or EEG manifestation of intraoperative seizure activity was evident in any of the patients who were monitored using TcMEP, including those patients with active seizure disorder. Following the surgical procedure, there was no documented increase in seizure activity.

Monitoring of spinal cord function during scoliosis surgery in children with CP-related spastic quadriplegia and active seizure disorder is feasible and was protective of

spinal cord function using a multimodality approach that includes both somatosensory and transcranial electric motor evoked potentials. The present study did not find evidence of elevated seizure incidence secondary to repetitive transcranial electric stimulation and suggests that history of seizures should not be considered an absolute contraindication for TcMEP monitoring in this patient population.

Acknowledgements The authors would like to acknowledge the contributions of Ali Fuat Karatas and Brian Burke.

Authors' contributions Conception or design of the work: MWS, SD, KGK, AJF, MCT, KJR, SAS. Acquisition, analysis, or interpretation of data for the work: MWS, SD, KGK, AJF, RZ, KJR, SAS. Drafting the work: MWS, SD, KGK, KJR. Revising the work critically for important intellectual content: MWS, SD, KGK, AJF, RZ, MCT, KJR, SAS. Final approval of the version to be published: MWS, SD, KGK, AJF, RZ, MCT, KJR, SAS. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: MWS, SD, KGK, AJF, RZ, MCT, KJR, SAS.

Funding The authors received no external financial support for the submitted work.

Availability of data and material Data are available upon reasonable request.

Code availability Not applicable.

Declarations

Conflicts of interest All authors have no relevant financial or non-financial interests to disclose.

Ethics approval Approval was obtained from the Nemours Institutional Review Board. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent to participate Not applicable.

Consent for publication Not applicable.

References

- Nash CL Jr, Lorig RA, Schatzinger LA, et al (1977) Spinal cord monitoring during operative treatment of the spine. *Clin Orthop Relat Res* 126:100–105
- DiCindio S, Theroux M, Shah S, et al (2003) Multimodality monitoring of transcranial electric motor and somatosensory-evoked potentials during surgical correction of spinal deformity in patients with cerebral palsy and other neuromuscular disorders. *Spine (Phila Pa 1976)* 28:1851–1855. <https://doi.org/10.1097/01.BRS.0000083202.62956.A8>
- Hilibrand AS, Schwartz DM, Sethuraman V, et al (2004) Comparison of transcranial electric motor and somatosensory evoked potential monitoring during cervical spine surgery. *J Bone Joint Surg Am* 86-A:1248–1253. <https://doi.org/10.2106/00004623-200406000-00018>
- Quraishi NA, Lewis SJ, Kelleher MO, et al (2009) Intraoperative multimodality monitoring in adult spinal deformity: analysis of a prospective series of one hundred two cases with independent evaluation. *Spine (Phila Pa 1976)* 34:1504–1512. <https://doi.org/10.1097/BRS.0b013e3181a87b66>
- Schwartz DM, Auerbach JD, Dormans JP, et al (2007) Neurophysiological detection of impending spinal cord injury during scoliosis surgery. *J Bone Joint Surg Am* 89:2440–2449. <https://doi.org/10.2106/JBJS.F.01476>
- Lall RR, Lall RR, Hauptman JS, et al (2012) Intraoperative neurophysiological monitoring in spine surgery: indications, efficacy, and role of the preoperative checklist. *Neurosurg Focus* 33:E10. <https://doi.org/10.3171/2012.9.FOCUS12235>
- Accadbled F, Henry P, de Gauzy JS, et al (2006) Spinal cord monitoring in scoliosis surgery using an epidural electrode. Results of a prospective, consecutive series of 191 cases. *Spine (Phila Pa 1976)* 31:2614–2623. <https://doi.org/10.1097/01.brs.0000240642.28495.99>
- Hammett TC, Boreham B, Quraishi NA, et al (2013) Intraoperative spinal cord monitoring during the surgical correction of scoliosis due to cerebral palsy and other neuromuscular disorders. *Eur Spine J* 22:S38–S41. <https://doi.org/10.1007/s00586-012-2652-x>
- Owen JH, Sponseller PD, Szymanski J, et al (1995) Efficacy of multimodality spinal cord monitoring during surgery for neuromuscular scoliosis. *Spine (Phila Pa 1976)* 20:1480–1488. <https://doi.org/10.1097/00007632-199507000-00007>
- Ashkenaze D, Mudiyan R, Boachie-Adjei O, et al (1993) Efficacy of spinal cord monitoring in neuromuscular scoliosis. *Spine* 18:1627–1633. <https://doi.org/10.1097/00004691-200210000-00008>
- Legatt AD (2002) Current practice of motor evoked potential monitoring: results of a survey. *J Clin Neurophysiol* 19:454–460. <https://doi.org/10.1097/00004691-200210000-00008>
- MacDonald DB (2002) Safety of intraoperative transcranial electrical stimulation motor evoked potential monitoring. *J Clin Neurophysiol* 19:416–429. <https://doi.org/10.1097/00004691-200210000-00005>
- Master DL, Thompson GH, Poe-Kochert C, et al (2008) Spinal cord monitoring for scoliosis surgery in Rett syndrome: can these patients be accurately monitored? *J Pediatr Orthop* 28:342–346. <https://doi.org/10.1097/BPO.0b013e318168d194>
- Bhasin TK, Brocksen S, Avchen RN, et al (2006) Prevalence of four developmental disabilities among children aged 8 years—Metropolitan Atlanta Developmental Disabilities Surveillance Program, 1996 and 2000. *MMWR Surveill Summ* 55:1–9.
- Yeargin-Allsopp M, Van Naarden BK, Doernberg NS, et al (2008) Prevalence of cerebral palsy in 8-year-old children in three areas of the United States in 2002: a multisite collaboration. *Pediatrics* 121:547–554. <https://doi.org/10.1542/peds.2007-1270>
- Comstock CP, Leach J, Wenger DR. Scoliosis in total-body-involvement cerebral palsy. Analysis of surgical treatment and patient and caregiver satisfaction. *Spine (Phila Pa 1976)* 23:1412–1424. <https://doi.org/10.1097/00007632-199806150-00022> (**discussion 1424–1425**)
- Hadjipanayis A, Hadjichristodoulou C, Youroukos S (1997) Epilepsy in patients with cerebral palsy. *Dev Med Child Neurol* 39:659–663. <https://doi.org/10.1111/j.1469-8749.1997.tb07359.x>
- Odding E, Roebroek ME, Stam HJ (2006) The epidemiology of cerebral palsy: incidence, impairments and risk factors. *Disabil Rehabil* 28:183–191. <https://doi.org/10.1080/09638280500158422>
- Singhi P, Jagirdar S, Khandelwal N, et al (2003) Epilepsy in children with cerebral palsy. *J Child Neurol* 18:174–179. <https://doi.org/10.1177/08830738030180030601>
- Edebol-Tysk K (1989) Epidemiology of spastic tetraplegic cerebral palsy in Sweden. I. Impairments and disabilities. *Neuropediatrics* 20:41–45. <https://doi.org/10.1055/s-2008-1071263>

21. Koop SE (2009) Scoliosis in cerebral palsy. *Dev Med Child Neurol* 51:92–98. <https://doi.org/10.1111/j.1469-8749.2009.03461.x>
22. MacEwen GD, Bunnell WP, Sriram K (1975) Acute neurological complications in the treatment of scoliosis. A report of the Scoliosis Research Society. *J Bone Joint Surg Am* 57:404–408

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.